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Exploration in the service of prospective control

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Abstract

We propose a sequential process of exploration that can account for perception-action coupling in infant locomotion. Each phase in the sequence is a process of obtaining progressively more information leading to a motor decision—exploration from a distance, exploration via direct contact, and exploration of alternative means. Quick glances and prolonged looking from afar serve to alert the perceiver to important changes in the terrain. Intentional touching and testing alternative ways to traverse an obstacle are only prompted when prior information indicates a potential threat to balance. We further propose that depth information is privileged because it can be detected from a distance more readily than other surface properties such as rigidity and friction. Studies of infants walking down slopes and across "hole/patch" transitions illustrate the important role of exploration in prospective control of locomotion. © 2000 Elsevier Science Inc. All rights reserved.

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1. Introduction

How are perception and action coupled so as to allow adaptive control of movements? The Gibsons (Gibson, 1969; Gibson, 1979) proposed that exploration is the link that couples perceptual information with motor control. In this paper, we argue that surprisingly little is known about the process of exploration in the service of prospective control of a most basic

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action—locomotion. Previous work with adults has focused on identifying various types of visual information which are sufficient for supporting adaptive locomotion. Previous work with infants has focused on describing exploratory movements and motor decisions as infants tackle challenging locomotor tasks. What is missing is a mechanistic account of the real-time process of exploratory movements giving rise to perceptual information and supporting motor decisions in a continuous perception-action loop. Based on the rich variety of spontaneous exploratory movements observed in infants' locomotion, we propose a sequential model of exploration that provides the basis for such a mechanistic account.

2. Adaptive control of action

Adaptive control of action is a continuous real-time process of planning movements within the context of an ever changing environment and body. Movements cannot be performed in the same way over and over because the biomechanical constraints on action are continually changing (Bernstein, 1967, 1996; Lashley, 1960; MacKay, 1982; Reed, 1982). The everyday environment is variable, unpredictable, and full of novel situations. The effective, physical propensities of the body can change from moment to moment (e.g., merely raising an arm changes the subtle biomechanics of maintaining balance). Even highly automatized, repetitive movements such as walking must be continually modified to suit the current demands of the particular motor context. Adaptive control of action refers to the extent to which ongoing movements are suited to changes in local conditions. It is what makes a football running back able to sidestep and accelerate past tacklers toward the goal line and what makes ordinary pedestrians able to modify ongoing gait patterns to navigate a tricky patch of ground.

Inspired by the work of Gibson (1966, 1979) and Bernstein (1967, 1996), contemporary research on motor control focuses on perception-action coupling. As Gibson first pointed out, perceptual information provides the basis for adaptive motor decisions. Movements are embedded in a continuous perception-action loop, wherein what we are doing now provides feedback for deciding what to do next (Gibson, 1979; Lee, 1993; Reed, 1982). Optimally, this feedback allows movements to be controlled prospectively ahead of time rather than reactively in response to an unexpected perturbation. Movements are prospective when adjustments are anticipatory, that is, made prior to contact with an impediment or moving target event (Gibson & Pick, 2000; Hofsten, 1993; Lee, 1993). They are controlled when the rate of errors is low. Prospective control means lifting a leg to clear the curb, rather than attempting to recover balance after tripping on the obstacle. It means anticipating a shift in the body's center of gravity before lifting the arms, rather than compensating after the fact for disrupted balance. Because movements are ongoing, oftentimes prospective and reactive control occur in concert. A slight misjudgment in planning requires reactive adjustments; reactive adjustments, in turn, provide new information for planning the next step prospectively.

3. Locomotion as a test case

Both Gibson (1958, 1979) and Bernstein (1967, 1996) focused on locomotion as a test case for understanding perception-action coupling in guiding actions adaptively. One reason to focus on locomotion rather than reaching or other types of movements is that locomotion is a fundamental skill for virtually every type of creature. Adaptive locomotion is not tied to a particular kind of body, movement, arrangement of perceptual organs, or environment. Worms and house flies, birds and bats, jelly fish and electric fish, human infants and Olympic athletes do it. Both Gibson and Bernstein assumed that an adequate theory of adaptive locomotion would be a general model with broad explanatory force.

A related reason to focus on locomotion is that adequate guidance is fundamental to animals' survival in a way that guidance of reaching or other movements of the extremities are not. Errors in prospective control can have more serious consequences—crashing into obstacles, losing balance, and falling down. Locomotion involves large displacements of the body and decisions are, in a sense, irrevocable. In walking, crawling, jumping, trotting, etc., the body moves a large distance relative to the size of the limbs. Once the center of mass moves over the supporting limb, there is a commitment to completing the step. Optimally, information about upcoming threats to balance is gathered and processed a few steps ahead to allow sufficient time to plan and execute the necessary adjustments.

The control problem is central, yet by its nature very complex. Variations in the size and clutter of the path and in the slope, rigidity, and friction of the ground surface change the biomechanical constraints on balance and propulsion. Similarly, affordances for locomotion are affected by variations in body mass, location of the center of mass, muscle strength and flexibility, and so on. For example, a shallow slope is easy to walk down when the ground is dry and compacted, but is treacherous when the surface is slick or loose. As degree of slant increases, the probability of successful walking decreases. A very steep slope is impassable under any conditions. Reciprocally, both temporary changes in body propensities and more permanent, developmental changes affect possibilities for action. The same slippery slope may be safe for walking in hiking boots but be impossibly risky in leather-soled shoes or while carrying a heavy load. A safe surface for healthy, young adults can be impossible for toddlers and elders.

4. Exploration

Exploration is the key to prospective control. One of the Gibsons' (Gibson, 1969; Gibson, 1979) important insights is that exploratory movements are the link in the perception-action chain. Here, we define exploration as movements which generate information or allow the perceiver to gather information relevant for planning future actions. Exploratory movements must be self-initiated (e.g., information generated from passive locomotion while an infant is being carried is not, by definition, the result of exploration). Exploratory movements include varying levels of attention. On one extreme of inattentiveness is spontaneous wiggles, thrashes, and stereotypies which generate information about the position of the limbs and body relative to gravity and the supporting surface. On the other extreme of focused attention are concerted, directed movements produced expressly for the purpose of generating or gathering additional information about possibilities for action. Situated somewhere in the middle of this continuum are casual exploratory scans (e.g., visual exploration while walking along an open road) and information generating movements which are the byproduct of another ongoing action (the walking movements themselves generate visual flow, vestibular, and kinesthetic information about the status of the body relative to the environment).

Significant progress has been made in identifying the manifold kinds of visual information available for prospective control of stance and locomotion in adults. For example, a recent special issue of *Ecological Psychology* (edited by Warren, 1998) focused on various patterns of optic flow information for visually guided locomotion. Numerous articles have been devoted to proposals and debates about optic flow information for controlling locomotion and balance (e.g., Bardy et al., 1996; Kirschen et al., 2000; Vanderberg & Brenner, 1994; Warren et al., 1991). Adults can use visual information for eyeheight to decide whether to walk frontwards or turn sideways to fit through narrow doorways (Warren & Whang, 1987) and to decide whether they can walk up stairs of different riser heights (Warren, 1984). Optic flow is sufficient for supporting adults' motor decisions about steering and heading (e.g., Gibson, 1958; Kirschen et al., 2000; Warren, 1998; Warren et al., 1991). Perhaps most impressive, a wealth of empirical findings shows that the rate of expansion in optic flow yields information about time to contact a surface in adults of a variety of species and in a variety of locomotor tasks—plummeting gannets deciding when to close their wings before diving into the water (Lee & Reddish, 1981), hummingbirds alighting on a flower (Lee, Reddish & Rand, 1991), flies landing on a target (Schoner, 1994), horses regulating their gait to jump over hurdles (Laurent, Dinh Phung & Ripoll, 1989), human athletes landing a somersault on a trampoline (Lee et al., 1992), regulating their gait during the run-up phase of the long jump (Lee et al., 1982), controlling their step length during running over irregular terrain (Warren et al., 1986), and timing a jump up to punch a falling ball (Lee et al., 1983).

Despite impressive progress identifying sources of visual information sufficient for supporting adults' motor decisions, few studies have described the types of exploratory movements adults spontaneously produce which might give rise to perceptual information. The evidence clearly shows that perceptual information is degraded when spontaneous exploratory movements are restricted. For example, Mark and colleagues (1990) asked whether adults could recalibrate their motor decisions to experimental manipulation of their leg length via platform shoes. When the participants were allowed to execute spontaneous shuffling, swaying, and small stepping movements between trials, they quickly recalibrated to their longer leg lengths. However, when spontaneous exploratory movements were restricted by making participants stand stiffly against the wall, errors and variability remained high across multiple trials.

In contrast to the literature on adult locomotion, research with infants has focused explicitly on describing babies' spontaneous exploratory movements when they are faced with challenging locomotor situations. Many labs have tested infants on the visual cliff and in other locomotor tasks such as traversing rigid and squishy surfaces, climbing up and down stairs, and going over, under, and around barriers (e.g., Campos et al., 1992; Campos et al., 1978; Gibson et al., 1987; Gibson & Walk, 1960; Palmer, 1987, 1989; Rader et al., 1980;

Richards & Rader, 1983; Schmuckler, 1996; Schmuckler & Gibson, 1989; Ulrich et al., 1990; Walk, 1966). In our labs, we have tested sitting, crawling, cruising, and walking infants at the edge of an apparent drop-off on a visual cliff, at the brink of a real drop-off on wide and narrow gaps in the floor, on mechanized walkways with steep and shallow slopes, navigating wide and narrow bridges spanning a precipice, steering around obstacles and barriers, descending stairs, and approaching slippery, squishy, prickly, and colored patches on the floor (e.g., Adolph, 1995, 1997, 2000; Berger et al., 2000; Berger et al., 2000; Eppler et al., 1997; Lo et al., 1999; Leo et al., 2000; Weise et al., 2000; Wendt et al., 1997).

5. Three types of exploratory behaviors

Across the varied tasks and developmental levels used to test adaptive locomotion in infants, three distinct types of exploratory behaviors emerged: exploration from a distance, exploration via direct contact, and exploration of alternative means. All three categories of exploration were observed across studies and labs. All three types of exploratory behaviors involve multiple perceptual systems and multimodal information. This is a functional classification based on the utility of obtained information rather than the more typical structural classification by sensory modalities.

5.1. Toddlers on slopes

We illustrate the categories of exploration with Adolph's (1995) study of 14-month-old toddlers' locomotion over slopes. We selected this study as the exemplar for several reasons. First, the test paradigm is a laboratory analogue of everyday locomotor challenges: A relatively consistent ground surface is interrupted by an abrupt change in terrain which requires gait adjustments or avoidance. (Note that nearly every study in the literature shares this common set-up. The alternative would be a ground surface which is variable on every step.) Second, the testing apparatus and design of the study permitted precise parametric scaling of individual infants' responses according to incremental changes in the slope of the surface. Third, infants' exploratory behaviors in this study were plentiful and elaborated, allowing for a rich description of the range of movements involved. Finally, infants' exploration was exquisitely differentiated according to the relative degree of risk accompanying each motor decision.

The testing apparatus was comprised of a flat starting platform for approaching the surface transition, a sloping middle section, and a flat landing platform that was raised and lowered to present slopes varying in 2° increments from 0° to 36° (see Fig. 1). Across a series of approximately 25 trials, infants stood at the far end of the starting platform with their attention directed to the slope. They were given 60 s to decide whether and how to descend to a parent coaxing them from the landing platform. An experimenter followed alongside infants to rescue them if they began to fall. A modified psychophysical staircase procedure (Adolph, 1995, 1997, 2000; Adolph & Avolio, 2000) was used to estimate the steepest slope each infant was physically capable of walking down without falling. Trials were coded online as a success (walked safely), failure (tried to walk but fell), or refusal (slid down or

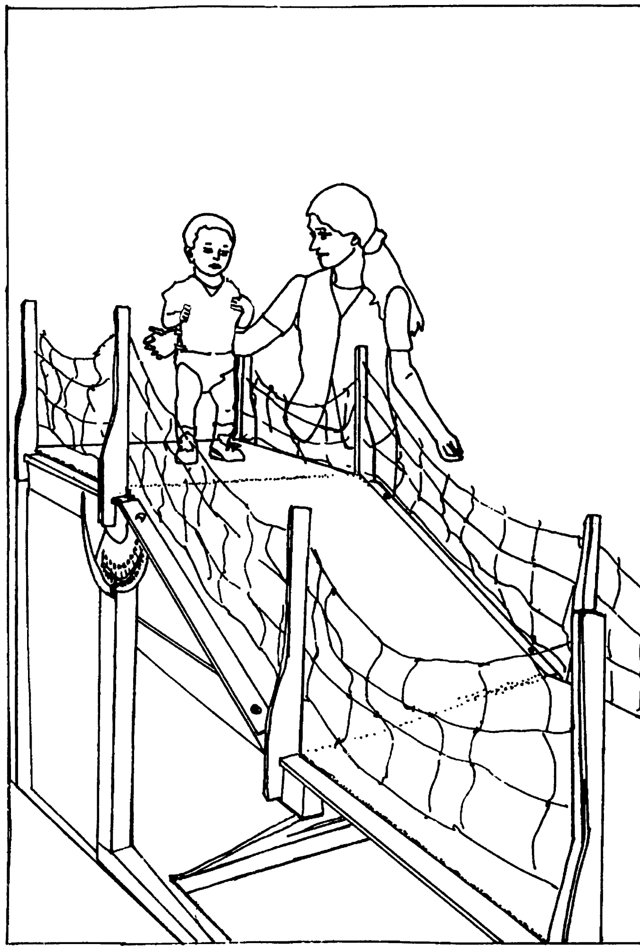

Fig. 1. Sloping walkway. Each section (starting platform, sloping middle portion, and landing platform) was 91 cm long x 84 cm wide. The slope was adjusted by means of a hydraulic pump raising and lowering the landing platform (range was from 22 to 75 cm high).

avoided descent). Slant was increased after successful trials and decreased after failures or refusals until converging on a "walking boundary" at a 67% criterion (i.e., steepest slope infant walked down successfully on ≥2/3 trials and failed or refused on ≥2/3 trials at all steeper increments).

In this age-held-constant design, infants showed a wide range of walking skill and a correspondingly wide distribution of walking boundaries on slopes (boundaries ranged from 6° to 28°). To take individual infant's walking abilities into account, we normalized degree of risk to each infant's walking boundary—slopes shallower than boundary were safe and slopes steeper than boundary were increasingly risky. We assessed the adaptiveness of infants' motor decisions based on their error rate. More specifically, we indexed error rate with a "walk ratio": (successes + failures)/(successes + failures + refusals). By definition, the walk ratio was 0.67 at the walking boundary, but it could vary freely on all other increments of slope. Also by definition, success was rare on slopes steeper than boundary, so walk ratios for risky slopes were based primarily on the proportion of failures to refusals. Thus, highly adaptive decisions would be indicated by attempts to walk when the probability of success was high (walk ratios near 1 on safe slopes) and refusals to walk when the probability of success was low (walk ratios near 0 on risky slopes). In contrast, maladaptive decisions would be indicated by attempts to walk on impossibly risky slopes. In sum, the adaptiveness of infants' decisions was indicated by how closely they matched their attempts to walk to the conditional probability of success.

Infants showed impressive prospective control in this task. They attempted to walk down safe slopes and refused to walk down risky ones. Fig. 2a shows walk ratios normalized by relative degree of risk to each infant's walking boundary. Walk ratios decreased steadily from boundary (0.94) to each increasingly risky slope (0.11 at $+18^{o}$). The walk ratio curve (solid line) closely matched the conditional probability of success (dashed line). On refusal trials, infants used a variety of descent strategies: sliding in a sitting position, backing down feet first, crawling on hands and knees, and sliding down headfirst. Most infants used multiple strategies across trials. Avoidance was rare.

Because degree of slant varied from trial to trial, infants' motor decisions had to be based on information they obtained at the beginning of each trial. We examined infants' actions leading up to their decision about how to cope with each slope. We found that infants produced three types of exploratory activity on the starting platform—exploration from a distance, exploration via direct contact, and exploration of alternative means—and that each type of exploration was related to relative degree of risk. As risk increased, so did each type of exploratory activity (Fig. 2b–d). It is important to note that, in principle, the type and amount of exploratory behavior produced could be independent of motor decisions. That is, infants could take only a momentary glance at a risky slope and correctly descend in an alternative sliding position. Or, they could engage in prolonged, elaborated bouts of exploratory behaviors and attempt to walk down impossibly risky slopes nonetheless.

5.2. Exploration from a distance

One kind of exploratory activity generates and gathers information from a distance, enabling perceivers to adjust steering and posture before encountering the surface transition. Echolocation, electrolocation, chemosensory perception, and sonar are examples of long distance probes. In humans, vision serves as the primary far-off sense. It is an active process of moving the eyes, head, and body (Gibson, 1979; Lee, 1993). Exploration from a distance always involves the natural swaying motions for maintaining balance. Oscillations of the body during stance and locomotion produce concurrent visual, vestibular, and somatosensory information about the current status of the body relative to the surface of support (Lee & Lishman, 1975; Stoffregen, 1985; Stoffregen & Riccio, 1988). Swaying and stepping, for example, produce accelerations in the vestibular apparatus, cause deformation and stretching of skin and joint receptors, and generate patterns of optic flow that specify the speed and direction of body movement. Peering over the edge produces motion parallax which specifies changes in depth of the ground. Visual texture gradients and other depth cues provide information about the location of the surface transition and the degree of slant.

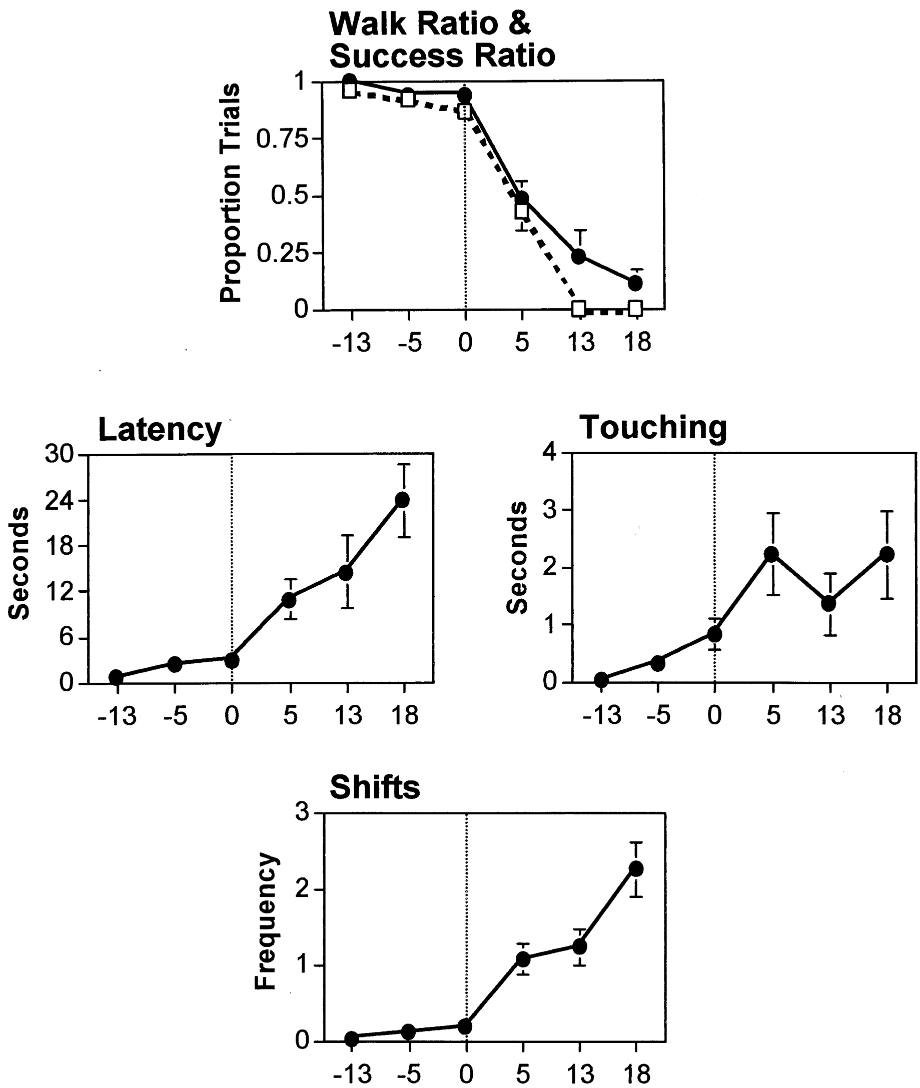

Fig. 2. Walk ratios and exploratory activity for toddlers on slopes. (a) Walk ratios (solid line) relative to the probability of success (dashed line). Slope boundary is indicated by 0 on the x-axis, slightly harder slopes by $+5^{o}$, moderately difficult slopes by $+13^{o}$, and impossibly risky slopes by $+18^{o}$. Negative numbers on the x-axis reflect increasingly shallower slopes relative to boundary. (b) Latency to embark onto the slope—exploration from a distance. (c) Duration of touching—exploration via direct contact. (d) Number of shifts in position—exploration of alternative means.

In the Adolph (1995) study, as in many other paradigms, toddlers began each trial facing the surface transition from a few feet away. This ensured at minimum a brief moment of visual exploration of the upcoming ground surface. On increasingly risky increments of slope, infants engaged in more prolonged exploration from a distance. While keeping their bodies away from the brink of the slope, they stood in place swaying gently back and forth,

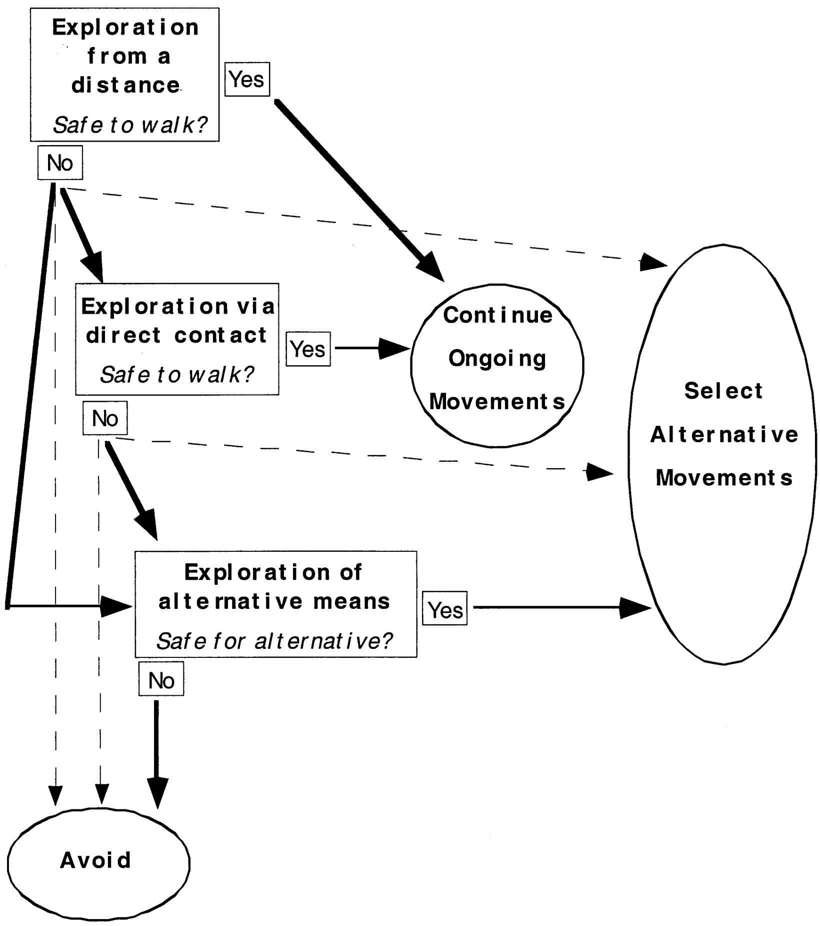

Fig. 3. Sequential process of exploration. Rectangles represent the three phases in our proposed sequence, each with choice points leading to further exploration (next rectangle) or a motor decision (represented by circles and ovals).

executed bouts of exaggerated stepping movements in place, and walked small distances over the starting platform—all the while, maintaining visual contact with the landing platform and the slope.

Due to the side-view camera angle in this study, it was not possible to conduct frame-by-frame coding of infants' eye gaze. Thus, we used a crude index of exploration from a distance: infants' latency to leave the starting platform. The latency measure is only a crude index because it includes other forms of exploration and nonexploratory displacement behaviors such as looking at the ceiling lights, pulling lint off the walkway carpet, and playing with their t-shirts or diapers. Nonetheless, in studies where it was possible to code eye gaze, the latency measure and visual inspection show similar patterns, with the looking curve displaced slightly downward from the latency curve (Fraisse et al., 2001). Fig. 2b shows that infants' exploration from a distance was discriminate and increased on risky slopes.

In other studies that reported either infants' looking behavior from a distance or their overall latency to begin crossing the test surface, exploration was similarly discriminating. Like toddlers, crawling infants also increase visual inspection from a distance and display longer latencies descending risky slopes (Adolph, 1997; Adolph et al., 1993; Fraisse et al., 2001). The same pattern of results holds true for crawling infants at the edge of a visual cliff (Campos et al., 1978; Eppler et al., 1997) and a real cliff (Adolph, 2000), crawling and walking infants approaching a rippling waterbed (Gibson et al., 1987), cruising infants challenged with gaps in the floor or a handrail used for support (Leo et al., 2000), walking infants descending stairs (Berger et al., 2000) and crossing bridges (Berger, McLaughlin & Adolph, 2000), and toddlers adjusting to experimental manipulation of their body dimensions as they coped with descending slopes (Adolph & Avolio, 2000).

5.3. Exploration via direct contact

A second kind of exploratory activity generates and gathers information via direct contact with the surface transition, enabling perceivers to test threats to balance before committing themselves to locomoting onto the surface. Touching with extremities such as hands, paws, and feet, or pressing against the surface with whiskers, antennae, or a blind person's cane are examples of exploratory probes involving direct contact. In human infants, touching with the extremity normally used for support (hands for crawlers, feet for walkers) is the primary manner of direct contact. Touching is nearly always accompanied by visual exploration. Test movements such as touching the juncture, straddling it with hands or feet and rocking vigorously over wrists or ankles, and taking a probing step onto the surface provide somatosensory and vestibular information about potential consequences for maintaining balance. The resulting muscle torque, shearing forces, patterns of optic flow, and accelerations in the vestibular apparatus give direct information about surface depth, friction, rigidity, and texture.

An important criterion for classifying movements of this type in babies is that the exploratory movements generate similar forces to the movements involved in actually navigating the transition. In many cases, the kinematics of exploratory and performatory movements are similar. For example, in Adolph's (1995) toddler study, many of the infants' exploratory movements at the brink of the slope closely corresponded to the action of walking downhill. Babies put their feet right at the brink of the slope or slightly over the edge and then made small stepping, swaying, and rocking movements in place. This form of touching is highly informative about the stability of the body relative to the slant of the surface. The small proportion of remaining touches involved using the hands to pat and probe the slope. In all cases, touching was simultaneous with looking as infants peered over the edge or gazed toward the landing platform. Fig. 2c shows that toddlers' exploration via direct contact (indexed by proportion of trials on which infants engaged in coordinated looking and touching) increased on risky slopes.

Other studies that reported exploration via direct contact revealed the same pattern of results. Crawling and walking infants of various ages and levels of locomotor skill engaged in more coordinated looking and touching on increasingly risky increments of slope (Adolph, 1997; Adolph & Avolio, 2000; Adolph et al., 1993; Fraisse et al., 2001), on a rippling waterbed compared with a rigid plywood surface (Gibson et al., 1987), and while descending stairs (Berger et al., 2000) and crossing narrow compared with wide bridges (Berger et al., 2000). In the tasks involving a cliff or gap in the surface of support, crawling infants explored the surface transition directly by stretching and retracting one arm over the precipice as they simultaneously leaned their bodies forward and backward at the brink (Adolph, 2000). Cruising infants similarly explored gaps in a handrail used for support or gaps in the floor beneath their feet by stretching and retracting an arm or a leg respectively over the gap (Leo et al., 2000).

5.4. Exploration of alternative means

A third kind of exploratory activity tests alternative means for navigating the surface transition, enabling perceivers to obtain information about the consequences of various methods of locomotion prior to selecting one. Means/ends exploration may include random thrashing or trial and error learning like cats in a Thorndike (1911) puzzle box, or selecting an alternative route after encountering an impasse like rats in a maze. However, when performed by primates, means/ends exploration is often goal directed and inventive. Like the means/ends exploration described by Piaget (1952) in object tasks, we found that infants often produce exploratory movements with a highly cognitive flavor in locomotor tasks. Exploration of alternative means may require infants to recognize an environmental prop as a tool, to sequence various movements into a coherent strategy, to extract viable strategies from trial and error, and in all cases, to view a movement as an intermediary means for achieving a goal. Like chimps and monkeys (Harlow & Mears, 1978; Kohler, 1925), human infants stack boxes, combine sticks, and create canes and handrails to augment balance control and extend locomotor capabilities (Berger et al., 2000; Berger et al., 2000; McGraw, 1935). When confronted with slopes, stairs, and cliffs, infants execute multiple shifts in position to test various descent strategies (Adolph, 1995, 1997). When confronted by an impassable obstacle, infants search for detours (Lockman, 1984; McKenzie & Bigelow, 1986; Wendt et al., 1997).

In the Adolph (1995) toddler study, infants explored alternative means by executing multiple shifts in position (e.g., shifting from standing to sitting to standing to backing), as if testing what different positions felt like before committing themselves to going. The backing strategy was particularly interesting because it required infants to turn away from the landing platform and move backward toward their goal. Often infants assumed the backing position on the starting platform, abandoned it, pivoted in circles on their stomachs and so on, as they tried to figure out the requirements of this difficult strategy. Another interesting form of means/ends exploration was infants' use of the supporting posts on the starting platform. On risky trials, infants often held onto a supporting post while touching the slope with their feet, or used the supporting post to switch positions as an adult would use a banister in a tricky situation.

Fig. 2d shows one measure of exploration of alternative means—discrete shifts in position on the starting platform. Avoidance required no shifts, and any of the various sliding positions required only a single shift. Thus, multiple shifts reflected a search for alternative means to descend. Shifts increased on risky slopes. Importantly, group averages exceeded 1.0

at every slope increment steeper than boundary. This suggests that infants explored alternative means for descending risky slopes rather than selecting a single strategy from their repertoire. Similarly, we observed an increase in means/ends exploration on risky increments in 11-month-old crawling infants descending slopes (Fraisse et al., 2001), in other studies with walking infants on slopes (Adolph, 1997), and in toddlers crossing bridges with and without a handrail for support (Berger et al., 2000). Campos and colleagues (1978) reported a similar finding with older crawling infants on the visual cliff. When challenged with the deep side over weeks of repeated testing, many babies invented a compromise strategy of skirting the open area of the cliff and hugging the wooden railings along the sides of the apparatus. As Piaget would have predicted, the youngest infants tested in studies which measured means/ends exploration did not show this kind of exploratory behavior. Despite demonstrating all the requisite component movements prior to testing, young crawling infants never tested alternative means or used alternative sliding positions to descend slopes (Adolph, 1997; Adolph et al., 1993).

6. Process of exploration: sequential model

We have described three kinds of exploratory behaviors displayed by infants in a wide range of locomotor tasks across several different laboratories. What is still missing, however, is a mechanistic account of the real-time process of exploration. That is, how might infants (or adults, for that matter) decide which exploratory movements to perform and when to culminate exploration in a motor decision? In this section, we describe a sequential model which is intended as a starting point for such an account. The model presupposes the everyday task of controlling locomotion when moving on a relatively consistent surface toward an abrupt disruption in the terrain. Unfortunately, to date, no researchers have reported sequential analyses of exploratory behaviors in locomotor tasks. Thus, our model is based on logical consideration of the requirements and benefits of the three types of exploratory behaviors displayed by infants.

We propose that exploration in the service of mobility must occur in a spatial and temporal sequence (Adolph, 1995, 1997; Adolph & Eppler, 1998). The sequence is both spatial and temporal because exploratory movements are logically ordered depending on the observers' proximity to the surface transition and on the observers' prior movements and efforts to gather information. Fig. 3 illustrates our sequential model. We have depicted the process of exploration as a flow chart with choice points to emphasize the serial nature and decision making aspects of prospective control. Each choice point represents a decision to continue exploring or to select a particular method of action (i.e., continue ongoing movements, choose an alternative movement, or cease activity). The flow chart does not imply that exploration is a lock-step progression where infants are forced through each phase of the sequence. Behavior is much too flexible and variable for that. However, we argue that exploration involving direct contact, exploration of alternative means, and the decisions to select an alternative movement or to avoid an obstacle can only occur intentionally if prompted by earlier information.

The first phase in the sequence is always exploration from a distance (top of Fig. 3).

Normally, long distance exploration occurs in the course of ongoing activity and involves low levels of attentiveness. Casual glances at the ground ahead can alert perceivers to important changes in terrain, thus prompting more focused visual inspection. Ongoing activity may continue at a slower pace or stop momentarily to allow for prolonged looking at the transition. If incidental glances and prolonged attentive looking indicate that the ground ahead is safe, then ongoing movements continue (exit via solid right arrow in the top of Fig. 3). If exploration from a distance indicates that the ground ahead is risky, then the decision is to select an alternative movement or avoid going (exit via dashed lines to end boxes in the sequence). But, if information obtained from a distance proves insufficient for supporting a definitive decision, then the perceiver is prompted to continue exploration to obtain additional information (solid downward arrows).

The second phase in the sequence is exploration via direct contact (middle of Fig. 3). Haptic and somatosensory exploration require perceivers to stop ongoing locomotion so as to probe the surface transition. Logically, intentional direct contact can only be elicited when previous information indicates a potential threat to balance control. Information obtained through direct contact may be more useful than visual information obtained from a distance because direct contact provides a closer simulation of the forces involved in the ongoing activity. Information gleaned from direct contact with a surface leads to the next choice point—continue ongoing movements (exit via solid right arrow in middle of Fig. 3), select an alternative movement or avoid going (exit via dashed lines to end boxes), or continue exploring (solid downward arrow).

The final phase in the sequence is exploration of alternative means (bottom of Fig. 3). Like direct contact, a deliberate search for new behavioral means would only be instigated if prior information suggested that balance control with the ongoing method of locomotion was threatened. If means/ends exploration does not yield an appropriate method for crossing, then perceivers are prompted to search for an alternate route. Exploring alternative means culminates in a decision to select an alternative movement (exit right arrow) or cease activity (exit downward arrow).

Although our model was inspired by the exploratory behaviors displayed by human infants in laboratory tasks, the model should generalize to infants and adults of any species who locomote through varied environments. The critical features of the model are the three kinds of exploration and their logical sequence in space and time. These features do not depend on any particular sensory apparatus or task. The model presumes a context where locomotion is challenged by a distant surface transition, because most of the time, ongoing locomotion consists of repetitive movements with only peripheral attention and casual scans for obstacles. However, the model can also account for situations when the terrain is more variable and monitoring is required from step to step (like picking one’s way across icy pavement). When the stakes are raised, attention becomes more focused, information-gathering is more concerted, and perceivers’ exploratory activity should consist more of direct contact and search for alternative means.

7. Depth information is privileged

A logical consequence of our sequential model of exploration is that certain surface properties may be more informative than others. If we are correct that exploration from a distance is always the first step in the sequence, then exploration in the service of locomotion should fail when visual cues from a distance do not elicit more informative methods of exploration. An interesting and nonintuitive prediction from our model is that depth information should be privileged as a long-distance elicitor of further exploration. Visual cues for changes in the depth of the terrain are reliable (upcoming slopes, cliffs, gaps, barriers, obstacles, corners, etc.). In contrast to depth, visual cues for surface rigidity and friction are unreliable. Squishy surfaces can be bumpy or smooth. Slippery surfaces can be shiny or matte. Moreover, surface rigidity and friction are not fixed properties of surfaces. Unlike degrees of slope or centimeters of height which can be detected without direct contact, rigidity and friction are defined only with reference to the forces acting on the surfaces. Rigidity depends on the amount, direction, speed, and surface area of the applied force (consider walking through wet snow in boots versus snowshoes). Coefficient of friction depends on the composition of the ground and the shoe, presence of contaminants, direction, speed and surface area of contact, etc. (walking over smooth linoleum when it is wet versus dry, in leather-soled shoes versus sneakers).

Unfortunately, rigidity and friction are ubiquitous surface properties. Given unreliable information from a distance, exploration may fail to evoke the appropriate response and walkers may stumble or fall. Our account explains why variations in surface friction—not depth—are the leading cause of accidents from falling in adults (Lin et al., 1995). Like stepping into quicksand, often walkers do not realize that a surface is slippery or pliable until they have already stepped onto it. Although exploration via direct contact would have been greatly informative, without reliable visual cues from a distance walkers would have no reason to initiate the appropriate exploratory movements.

Most previous work on prospective control of locomotion in infants involved depth manipulations which could be seen from a distance, such as slopes, cliffs, stairs, and obstacles. Even the study of surface rigidity (Gibson et al., 1987) involved visual events that could be seen from a distance (an assistant jiggled the waterbed surface from underneath creating ripples). Several "hole/patch" studies directly compared infants' responses to depth transitions (a hole) with their responses to surface changes which did not involve depth (a patch with varying friction, texture, or color) (Gibson et al., 1987; Gibson & Schmuckler, 1989; Weise et al., 2000). For example, Gibson and Schmuckler (1989) constructed a patch surface by placing a 46 cm x 46 cm brown cardboard patch over a raised checkerboard surface covered with Plexiglas. They constructed a hole by covering the entire walkway with brown cardboard and cutting a hole where the patch had been placed so that the checkerboard surface was visible three feet below. The toddlers in this study responded differentially and appropriately to the hole versus patch surface transitions. All 16 toddlers walked directly over the cardboard patch. In the hole condition, 11 infants detoured around the apparent discontinuity in depth.

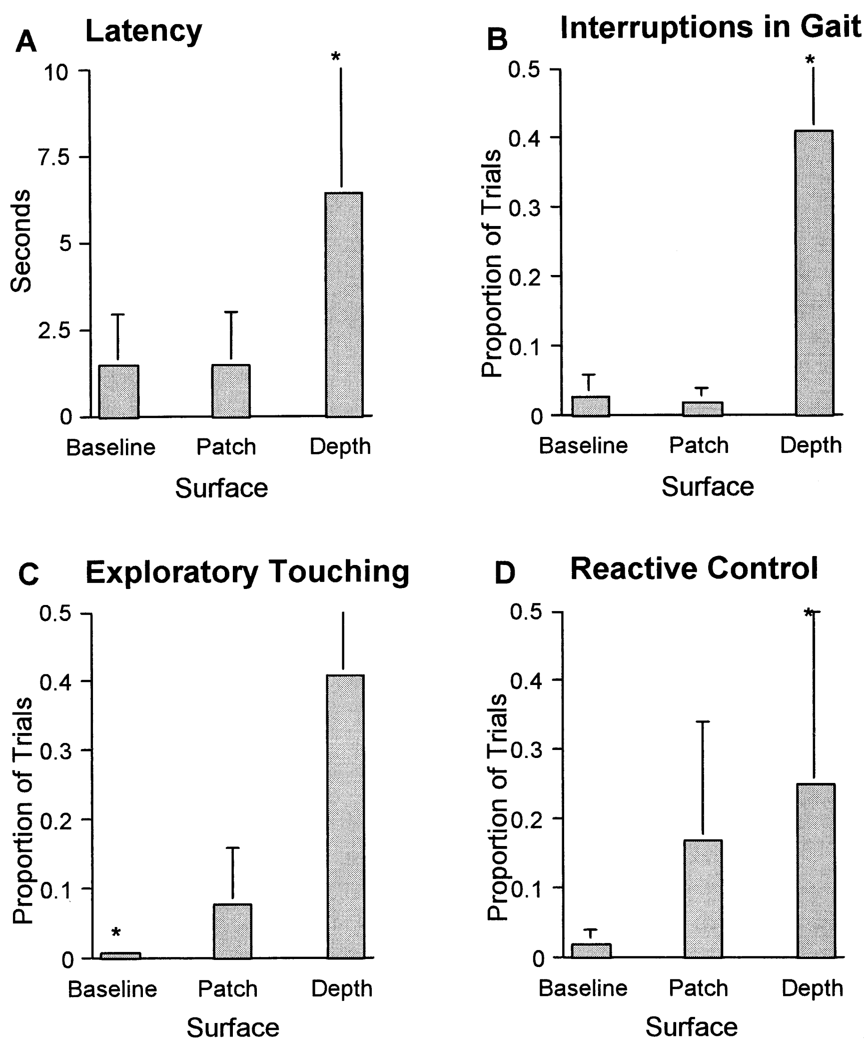

Fig. 4. Exploration for toddlers in the hole/patch study. (a) Latency to step onto the surface transition—exploration from a distance. (b) Interruptions in gait (halting forward progress prior to stepping onto the surface transition)—exploration from a distance. (c) Touching the surface—exploration via direct contact. (d) Reactive Exploration—distinguishing the surface transitions from baseline (continuous surface).

7.1. Exploration of depth versus other kinds of surface transitions

In a similar vein, we examined infants' exploratory activity as they approached a variety of 30.5 cm square patch surfaces located in the center of a raised carpeted walkway (Weise et al., 2000). We compared exploration for three kinds of patches: baseline patch that matched the surrounding blue carpet, transitions in depth (Plexiglas covering a hole cut into the carpet; 15 cm tall stair), and transitions in color, shine, and texture (beige carpet; shiny, green, marbled tile; nubby, black, rubber mat). Fig. 4 shows that across various measures of prospective exploration, infants responded most often to the two surfaces that involved a transition in depth (i.e., hole and stair) and least often to baseline and test patches (i.e., carpet, tile, mat). Latency to step onto the patch with both feet was a crude index of visual exploration from a distance. Infants displayed longer latencies while approaching the depth surfaces than the patch or baseline surfaces (Fig. 4a). Interruptions in gait (halting forward progress) indicate whether infants stopped for a bout of prolonged looking before crossing the transition. Interruptions were more frequent on the depth surfaces compared with patch and baseline surfaces (Fig. 4b). Touching the surface with feet or hands indexed exploration via direct contact. Again, only depth differed from patch and baseline (Fig. 4c).

Compared with the high levels of exploration displayed on the sloping walkway in Adolph's (1995) study, levels of exploration in this study were depressed. This was probably due to differences in size of the surface transition for the two studies. We developed a measure of reactive exploration to check whether infants were at all sensitive to the properties of the patch surfaces. Reactive exploration involved halting ongoing forward locomotion after stepping onto a patch. Infants were twice as likely to stop after stepping onto the patch surfaces relative to baseline, indicating that they perceived both depth and patch surfaces as different from the continuous baseline surface (Fig. 4d). Thus, it is not the case that infants failed to perceive the patch surfaces, but rather that they were not prompted to engage in prospective exploration.

Even a very small obstacle (an apparent hole or raised stair) specified by depth cues is sufficient to elicit prospective exploration from a distance. In contrast, when the transition involves only a change in color, shine, or texture, infants show no noticeable slowing or gait disruptions while walking straight ahead prior to stepping onto the surface. Perhaps it is more adaptive in the long run to respond selectively to depth cues because otherwise walkers would be compelled to interrupt gait every few steps to scrutinize a visual discrepancy. In the short run, walkers may err on surfaces with extreme variations in friction and rigidity. Compared to toddlers on slopes, infants in the hole/patch studies engaged in minimal touching and testing of alternative means. One reason for this difference is that consequences for losing balance were considerably less severe for a small patch on the ground relative to a substantial transition spanning the entire width of the ground surface. The important finding here is that infants were only prospectively responsive to changes in depth, and not to other transitions in the ground surface. In both slopes and hole/patch studies, infants detected this threat to balance control from a distance.

Similarly, toddlers may not respond prospectively to variations in surface friction or rigidity without guided direct contact. When placed directly onto a squishy foam surface or a slippery plastic surface, toddlers responded adaptively by gripping onto supporting posts or sitting down (Stoffregen et al., 1997). But when placed in front of a rippling waterbed, many infants failed to show adaptive prospective control. They attempted to walk onto the squishy surface and fell, subsequently completing traversal in a crawling position (Gibson et al., 1987; Gibson & Schmuckler, personal communication). When placed several steps in front of a slippery slope, toddlers responded only to changes in depth but not to changes in surface friction (Lo et al., 1999). Even after falling repeatedly on the slippery surface, infants apparently could not relate the cues for surface friction with the consequences for balance control. However, when the slope was sufficiently steep to elicit deliberate touching, infants made adaptive decisions about how to descend. In sum, depth cues elicit more prospective exploration from a distance than other visual cues even when the latter are made more salient.

8. Caveats: changes with development

Despite researchers' recent emphasis on perception-action coupling in understanding the development of adaptive motor control, surprisingly little work has examined the behaviors which drive the perception-action loop. Observations of infants coping with novel challenges to balance control is instructive. Infants' rich variety of exploratory movements give rise to multimodal sources of information about balance control relative to the properties of the ground surface. We proposed that exploratory activity must occur in a sequence. It is a continuous, step by step process of acquiring the necessary perceptual information for making adaptive motor decisions. In the course of locomotion, long distance cues elicit further exploratory movements via direct contact. Thus, depth information may be privileged.

We conclude with three caveats which point toward directions for further research on the development of adaptive locomotion. First, our sequential model is based on a logical consideration of the three kinds of exploratory movements displayed by infants. The strongest empirical test of our sequential model, of course, would be sequential analyses of online exploratory behaviors. Such analyses require labor intensive time coding of the onsets and offsets of each type of exploration during the course of each trial. These analyses are currently underway in our labs.

Second, our argument is that generating and selecting appropriate exploratory movements is only a *necessary* prerequisite for prospective control of locomotion. Appropriate exploratory movements may not be *sufficient* for adaptive prospective control. In early stages of motor skill acquisition, infants often engage in prolonged and varied exploration and still err (e.g., stumble down a steep hill, blunder onto a waterbed, fall into a large gap or venture onto the visual cliff), as if they do not yet understand how to use the information to guide their decisions (Adolph, 1997, 2000; Adolph et al., 1993; Campos et al., 1992, Campos et al., 1978; Eppler et al., 1997; Gibson et al., 1987; Leo et al., 2000; Rader et al., 1980; Richards & Rader, 1983). Adaptive control of locomotion requires a lengthy learning process, where infants must discover the limits of maintaining balance in various postures. They must learn to relate perceptual information generated by exploration to consequences for balance control.

A final caveat highlights the need for further developmental research. As stated eloquently in the theories of major developmentalists, perceptual exploration itself undergoes important developmental changes (e.g., Gibson, 1988; Gibson & Pick, 2000; Piaget, 1952, Thelen & Smith, 1994). With advent of new motor skills, infants' attention shifts to new aspects of the environment and new exploratory movements become available. With practice, exploratory movements become more refined and efficient. In fact, one benefit of studying infants' exploratory movements rather than those of adults is that babies' movements are easier to observe. Infants' efforts to explore tend to involve larger and more discernible movements than adults' sophisticated and subtle exploratory movements. Thus, research on how exploration binds perception with action is only a first step toward understanding the development of adaptive motor control.

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